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Improving Computer Simulations of Heat Transfer for Projecting Fenestration Products: Using Radiation View-Factor Models

Brent Griffith

Dragan Curcija, Ph.D.
Member ASHRAE

Daniel Türler

Dariush K. Arasteh, P.E.
Member ASHRAE

ABSTRACT

The window well formed by the concave surface on the warm side of skylights and garden windows can cause surface heat-flow rates to be different for these projecting types of fenestration products than for normal planar windows. Current methods of simulating fenestration thermal conductance (U-factor) use constant boundary condition values for overall surface heat transfer. Simulations that account for local variations in surface heat transfer rates (radiation and convection) may be more accurate for rating and labeling window products whose surfaces project outside a building envelope. This paper, which presents simulation and experimental results for one projecting geometry, is the first step in documenting the importance of these local effects.

A generic specimen, called the foam garden window, was used in simulations and experiments to investigate heat transfer of projecting surfaces. Experiments focused on a vertical cross section (measurement plane) located at the middle of the window well on the warm side of the specimen. The specimen was placed between laboratory thermal chambers that were operated at American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) winter heating design conditions. Infrared thermography was used to map surface temperatures. Air temperature and velocity were mapped throughout the measurement plane using a mechanical traversing system. Finite-element computer simulations that directly modeled element-to-element radiation were better able to match experimental data than simulations that used fixed coefficients for total surface heat transfer. Air conditions observed in the window well suggest that localized convective effects were the reason for the difference between actual and modeled surface temperatures. U-value simulation results were 5% to 10% lower when radiation was modeled directly.

INTRODUCTION

Computers are routinely used to model heat transfer through windows in order to generate values for rating and labeling the thermal performance of window products. Routine modeling uses special-purpose software that is comparatively simple to run (Arasteh et. al. 1993; Finlayson 1993; Arasteh et al. 1996; EE 1991; UW 1992; and WIS 1994). Detailed research models also exist that use considerable time and computing resources (Curcija 1992; Zhao et al. 1996; de Abreu et al. 1996). Advances in computer and software technologies may allow detailed simulations to be used in future routine modeling. This could improve the fairness of product performance ratings and provide new types of information, such as surface temperature distribution or dynamic thermal response.

A typical simulation predicts steady-state heat flow through a window under the environmental conditions used in laboratory hotbox physical testing. The conditions can be described by the bulk air temperature away from the window and a mean total surface heat-transfer coefficient. Typical conditions for designing winter heating systems use bulk air at −18°C (0°F) and a total film coefficient of 30 W/m^2·K (6 Btu/h·ft^2·°F) on the window's cold side and 21°C (70°F) and 8 W/m^2·K (1.5 Btu/h·ft^2·°F) on the warm side. Computer simulation programs use such values as constants when characterizing boundary conditions for a particular surface that meets air. Use of fixed film coefficients usually is necessary because the detailed data that describe local film coefficients are difficult to measure or not available.

Film coefficients actually vary locally. If local conditions are not used in modeling, the accuracy of simulations for fenestration with projecting surfaces is compromised. The total film coefficient has a convective portion and a radiative portion; each has an approximately similar magnitude for the natural convection conditions on the warm side of windows.

Brent Griffith is a principal research associate, **Daniel Türler** is a senior research associate, and **Dariush K. Arasteh** is a staff scientist in the Building Technologies Program, Lawrence Berkeley National Laboratory, Berkeley, Calif. **Dragan Curcija** is president of Carli Inc., Amherst, Mass.

However, for projecting fenestration products, the radiative part of the overall film coefficient is lower because the net radiation from the surrounding enclosure onto the surfaces of the window well is reduced by the interaction of the self-viewing surfaces on the concave, warm side. (Self-viewing surfaces are those that can, in a literal sense, "see" each other because radiation can travel between them.) The presence of self-viewing surfaces almost always creates significant local variation in surface radiation, in contrast to the conditions for normal planar windows that have more uniform radiative exchange with the surrounding enclosure. The convective part of the overall film coefficient is determined by the temperature and flow of the ambient air adjacent to a window's surface. Airflow in the window well of a projecting window can differ from that of normal planar windows because of the projecting fenestration's geometric isolation and mix of glazing orientations.

The accuracy of computer simulations can be evaluated by comparison with measured local temperature data. Most window simulation models have been validated by comparing results to hotbox measurements of U-factors. Sometimes sophisticated computer modeling programs are validated by comparing the programs' solutions for common benchmark problems (such as heat flow from a flat plate) to experimental and/or analytical solutions. Infrared (IR) thermography, a nonintrusive experimental technique for gathering detailed maps of surface temperature (Griffith et al. 1995; Türler et al. 1997), has been used in the past to evaluate the accuracy of computer simulations. A 1996 study of insulated glazings undergoing steady-state heat flow compared IR t8hermography data to results of sophisticated computer simulations that modeled glazing gaps in detail (de Abreu et al. 1996; Griffith et al. 1996; Zhao et al. 1996). Although infrared measurements do not provide heat flow or conductance data, the detailed surface temperature data are useful for determining how closely a model approximates actual conditions. Infrared thermography also can be used to evaluate localized heat transfer phenomena that are important in the deep projecting geometry typical of a garden window or a skylight.

This paper explores the potential for improving the accuracy of heat transfer simulations of skylights and garden windows by directly modeling radiative heat transfer at the window's interior surface. Warm-side surface temperature results are presented from both simple and complex computer models and compared to experimental IR thermographic data. Simulation results for U-factors also are presented. The box-shaped specimen that was modeled and measured is made of foam board and acrylic sheet and is a simplified version of a garden window. Laboratory-based experimental measurements used infrared thermography to gather surface temperatures and a traversing system to map air conditions throughout a vertical measurement plane at the middle of the window well on the warm side of the specimen.

SPECIMEN

The foam garden window is a thermal test specimen specially prepared as a simplified version of a garden window. The design was created to investigate localized heat transfer phenomena at the window's warm-side surface without the complicating effects of heat flows inside the gaps of insulated glazings.

The foam garden window is made of 19.3 mm (3/4 in.) extruded polystyrene foam board (XEPS) and 4.7 mm (3/16 in.) acrylic sheet. The acrylic forms a simple open box, and the foam is adhered to it on the window's cold side. Foam joints are sealed with vinyl tape. The acrylic sheet is only on the window's warm side. Figure 1 diagrams the specimen and its mounting for thermal testing. When viewed from the warm side, the specimen has a square opening that is 902 mm (35.5 in.) high and 305 mm (12 in.) deep. The surround panel is 51 mm (2 in.) thick XEPS. The acrylic sides of the box extend all the way to the warm-side surface, flush with the rest of the surround panel.

COMPUTER SIMULATIONS

The two types of computer simulations presented here differ in their methods of modeling surface boundary conditions; the two methods are referred to as (1) fixed coefficient and (2) radiation view-factor. The fixed-coefficient data are generated using the computer program THERM, version 1.02. THERM is a two-dimensional conductive heat-transfer program based on the finite element method that was developed especially for modeling windows. (It is documented in Finlayson 1996). The radiation view-factor data are generated using a developmental (beta) version of THERM 2.0. The mesh used to represent the foam garden window is the same

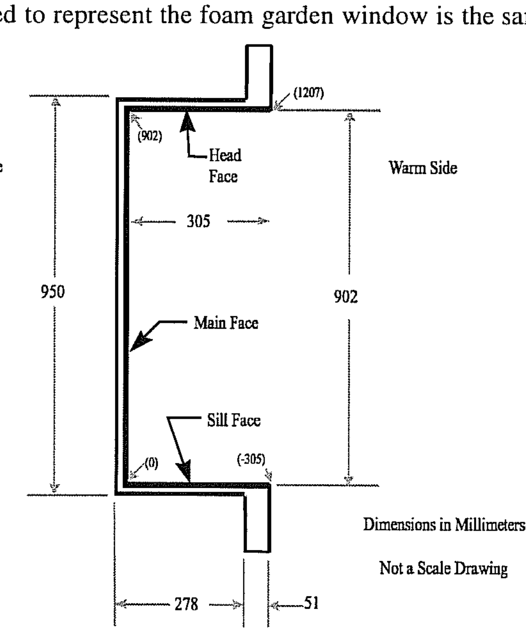

Figure 1 *Foam garden window cross section, dimensions, and mounting.*

TABLE 1
Boundary Conditions Used in Computer Simulations

		Fixed Coefficient THERM 1.02	Radiation View-Factor THERM 2.0
Warm Side	Temperature (°C)	21.1°	21.1°
	Convection Coef. (W/m^2·K)	2.76	2.76
	Radiation Coef. (W/m^2·K)	5.05	N/A
	Total Coef. (W/m^2·K)	7.81	N/A
Cold side	Temperature (°C)	–17.8°	-17.8°
	Convection Coef. (W/m^2·K)	20.58	20.58
	Radiation Coef. (W/m^2·K)	4.98	N/A
	Total Coef. (W/m^2·K)	25.56	N/A

for both types of simulations and was automatically generated using THERM.

Table 1 lists the boundary conditions used for both simulations to model heat flow through the foam garden window. The two simulations use the same convection coefficient, but the radiation view-factor simulation solves for radiative heat flow directly instead of using a constant coefficient. Table 2 lists the thermal conductivity and emittance values used to describe materials in the foam garden window specimen.

TABLE 2
Material Properties Used in Computer Simulations

	k Thermal Conductivity W/m^2·K	ε Emittance
Foam (XEPS)	0.03	0.9
Acrylic Sheet	0.11	0.9[a]

a. The value for the emittance of acrylic was estimated at 0.9, based on laboratory measurements using an 8-12 µm thermal imager and techniques described in Türler et al. (1997).

Radiation View-Factor Solution Method

THERM 2.0 uses a finite element method to solve two-dimensional conductive and radiative heat transfer problems for arbitrarily shaped geometries. The finite element solver in THERM 2.0 is derived from the public-domain computer programs TOPAZ2D and FACET (Shapiro 1983, 1986, 1993). A brief overview of the solution method used in THERM 2.0 is presented in Finlayson et al. (1995). View factors are calculated using the cross-string rule; this procedure is discussed in Curcija (1997).

For radiation boundary conditions, THERM 2.0 assumes that radiation surface segments are gray and isothermal and that view factors depend on geometry only. For two-dimensional geometrics, modeled here, Hottel's cross-string method (Hotell and Sarofim 1967) is used with shadowing algorithm for partially or fully obstructing surfaces. This procedure is described in Curcija (1997).

EXPERIMENTS

Experimental measurements focused on mapping the distribution of temperatures on and near the warm side of the foam garden window under steady-state heat-flow conditions. Separate experiments used a calibrated transfer standard to help determine environmental conditions during the testing. Special thermographic procedures were used to conduct infrared temperature measurements of the specimen to account for the effects of its self-viewing surfaces.

Apparatus and Procedures

Two laboratory environmental chambers were used to establish heat flow through the specimen in a fashion similar to that used in hotbox testing for winter heating conditions. The warm chamber, however, is a thermographic chamber designed for an unobstructed view of the specimen and therefore does not employ a baffle in the way that a hotbox does. The chambers and related instrumentation are described elsewhere (Türler et al. 1997).

Figure 2 shows the measurement plane of the foam garden window and the specimen's orientation to the warm chamber. The cold-side chamber moves air up the back (all five faces) of the specimen in a plenum; velocity was about 4.5 m/s at middle of the main face during the measurements. On the warm side, air is slowly circulated through a subfloor where temperature conditioning occurs. An air sink below the specimen removes cooled air. The air sink opening is 47 mm wide, and, for these measurements, it had a maximum air velocity of 0.79 m/s and a mean velocity of 0.52 m/s. Air is removed from underneath the specimen at a rate of 0.025 m^3/s per unit length of the slot (0.025 m^2/s in two dimensions).

Specimen surface temperatures were measured using IR thermography and an external referencing technique. Detailed discussion of the equipment and techniques developed for this purpose are presented elsewhere (Griffith et al. 1995, 1996; Türler et al. 1997). The thermographic measurements presented here were more complicated because the specimen

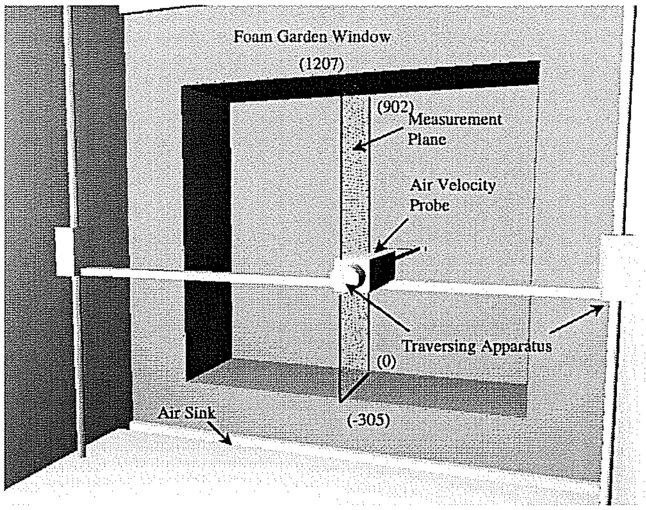

Figure 2 *Foam garden window experimental setup: measurement plane in the window well.*

surface is not flush. These procedures are discussed below because earlier, similar research did not address the complexities caused by self-viewing surfaces. External referencing of the IR data used a target with an acrylic surface that was controlled by circulating water through a copper plate.

The geometric isolation of the window-well air and the presence of heat and mass flow may cause conditions that deviate from the ambient conditions controlled by the warm chamber. A three-dimensional traversing system was used in the warm chamber to mechanically move a temperature probe and an air velocity transducer to gather data throughout the measurement plane. Spatial resolution was about 10 mm (0.4 in.). Air temperature data were gathered using a type-T thermocouple (special-limits, 30-gauge wire) All thermocouples were precalibrated at their operating temperatures. Air velocity data were gathered using a general purpose hot-wire anemometer. This velocity probe is a poor choice for this application because of its directional sensitivity, large size, self-induced flow, and poor accuracy over the range being measured. However, it was the only system available for use at the time. These velocity measurements should, therefore, be considered preliminary and should be repeated; we are currently investigating alternatives. The probe was horizontal, parallel to the main face of the specimen, so that it was primarily sensitive to the vertical component of airflow. Separate experiments were conducted to evaluate the probe's sensitivity to pitch and yaw.

Environmental Conditions

Although the environmental chambers are controlled to provide repeatable conditions and steady-state heat transfer, the actual conditions for each particular test vary slightly from standard ASHRAE design conditions. Environmental conditions are summarized concisely by reporting air temperatures and mean surface heat-transfer coefficients or film coefficients. Chamber operation settings can be varied to provide some control over airflow and film coefficients delivered to the specimen. The settings we used were selected based on the results of separate experiments that used a calibrated transfer standard (CTS) to directly measure film coefficients. Table 3 reports the results of CTS measurements conducted after the foam garden window tests along with the available data for conditions during the tests.

The planar CTS used here is constructed from 25.4 mm (1 in.) thick expanded polystyrene foam board that is sandwiched between 4.7 mm (3/16 in.) glass sheets. The 900 mm^2 (35.5-$in.^2$) CTS has a total thickness of 35 mm (1 3/8 in.) and is mounted flush on the warm side in a 39.4 mm (1.5 in.) thick surround panel made of XEPS. Thermocouple arrays located at each internal surface provide heat flow and temperature data, so the total film coefficients, which are mean values for the entire specimen surface, can be determined. Bulk air temperature values are averages for the warm and cold sides, respectively, and are derived from direct contact measurements using 100-Ω platinum resistance thermometers. The total film coefficient is separated into convective and radiative parts by using an analytical view-factor method to calcu-

TABLE 3
Environmental Conditions

		Planar CTS	Foam Garden Window
Warm Side	Temperature (°C)	21.2°	21.1°
	Convection Coef. ($W/m^2 \cdot K$)	3.4	N/A
	Radiation Coef. ($W/m^2 \cdot K$)	4.5	N/A
	Total Coef. ($W/m^2 \cdot K$)	7.9	N/A
	Air Sink Max. Velocity (m/s)	0.87	0.79
Cold Side	Temperature (°C)	−17.7°	−17.8°
	Convection Coef. ($W/m^2 \cdot K$)	29.6	N/A
	Radiation Coef. ($W/m^2 \cdot K$)	3.0	N/A
	Total Coef. ($W/m^2 \cdot K$)	32.6	N/A
	Air Velocity (m/s)	4.7	4.5

late the radiation portion and subtracting to obtain the convection portion. Note that significant local variation in film coefficients, which is the focus of this paper, also is present in these experiments. The difference between the thermal performance of the foam garden window and the CTS will result in different film coefficients during experiments. Because overall heat flow through the foam garden window was not metered, no reasonable method of estimating the "as tested" film coefficients is available at the time of this writing.

Complex Background Thermography

For infrared measurements of flat, flush-mounted specimens, there is no way for the different parts of the specimen surface to directly exchange thermal radiation. However, when a specimen has self-viewing surfaces, as shown in Figure 3, the background radiation level for certain measurements is affected by other portions of the specimen. If we assume that reflections are specular, the background radiation involved in an infrared temperature measurement of point A in Figure 3 will originate from point B. Point B is on the specimen. Thus, the background radiation level for point A depends on the temperature at point B, which will differ from the enclosure surface temperature. Special procedures and postprocessing are required to use infrared thermography on specimens with self-viewing surfaces. Thus, we refer to the technique for measuring self-viewing surfaces as complex background thermography.

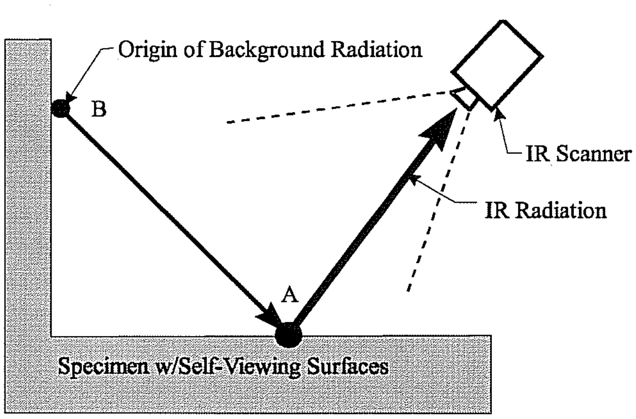

Figure 3 Complex background thermography.

In complex background thermography, the equations that govern calculation of infrared temperatures (Türler et al. 1997) are assumed to apply; however, radiosity and irradiance data are analyzed for each individual data point so that a distinct value for the level of background radiation is used for each datum rather than a single value for background radiation for the entire thermogram. Thus, the postprocessing of infrared data becomes complex and is performed entirely outside the thermographic software using a spreadsheet program.

Experimental procedures were developed to collect arrays of background thermal radiation data by using mirrors. Mirrors are applied directly to specimen surfaces to allow measuring of background radiation for those particular surfaces. For the situation in Figure 3, a mirror would first be applied to surface A after the specimen has been measured. Then, after the mirror reflections at surface A are captured, the mirror would be removed and a new mirror applied to surface B. Thermal equilibrium must be established between each step, and the scanner viewing angle and specimen geometry must stay the same. Because the only method currently available for directly gathering background radiation with the infrared scanner uses a specular mirror, it is necessary to assume that specular reflections also apply to measurements of diffusely reflecting surfaces, such as wood. The error in determining the background radiation level on diffuse surfaces may be significant, warranting investigations of background mirrors that can approximate diffusely reflected radiation levels.

RESULTS

Surface Temperatures

Results for surface temperatures on the warm side of the foam garden window are shown in Figure 4. The vertical axis of Figure 4 shows location on the specimen surface as accumulated distance from the sill corner, in millimeters. The lower surface of the specimen (the sill face in Figure 1) extends from −305 mm to 0 mm. The main vertical face of the specimen extends from 0 mm to 902 mm, and the upper horizontal surface (the head face in Figure 1) extends from 902 mm to 1,207 mm.

Three sets of data are plotted in Figure 4, comparing the experimental measurements using IR thermography, simulation using fixed film coefficients, and simulation using view-factor radiation modeling. The absolute uncertainty in the IR data is estimated at ±4 mm (vertical axis) and ±0.7°C (horizontal axis). The method to determine uncertainty is described in Türler et al. (1997). Spot thermocouple measurements were made and confirmed the shape of the temperature curve determined with IR thermography. However, given that the placement and mounting of thermocouples and wires can affect readings, and that this affect is not known, we did not pursue this extensively.

Figure 5 shows the same data as Figure 4 but plots a narrower range that focuses on the results for the sill corner and shows an error band for the estimated uncertainty in the IR data. Similarly, Figure 6 shows the results for the head corner in greater detail.

Window Well Air Conditions

The window-well air is the volume of air located in the concave region of the warm side of a projecting window or similar fenestration. A traversing system was used to measure a vertical plane, called the measurement plane, at the middle of the window well. Data for air temperature and velocity were gathered for specific locations on a 10 mm grid covering the

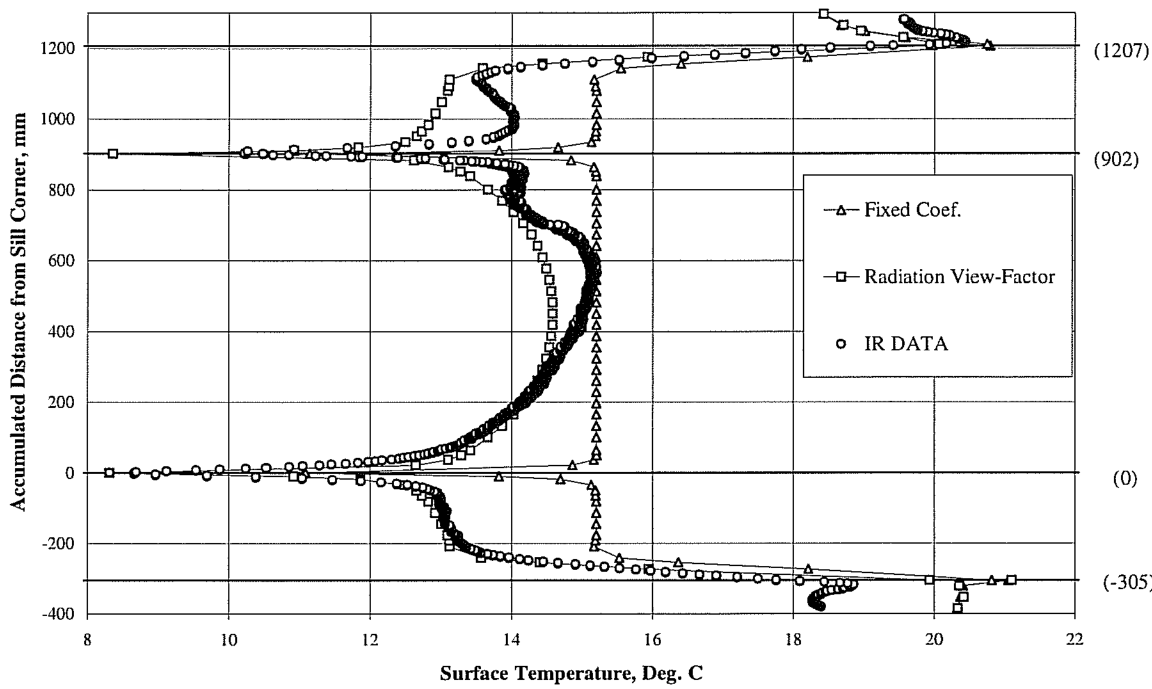

Figure 4 *Surface temperature of foam garden window.*

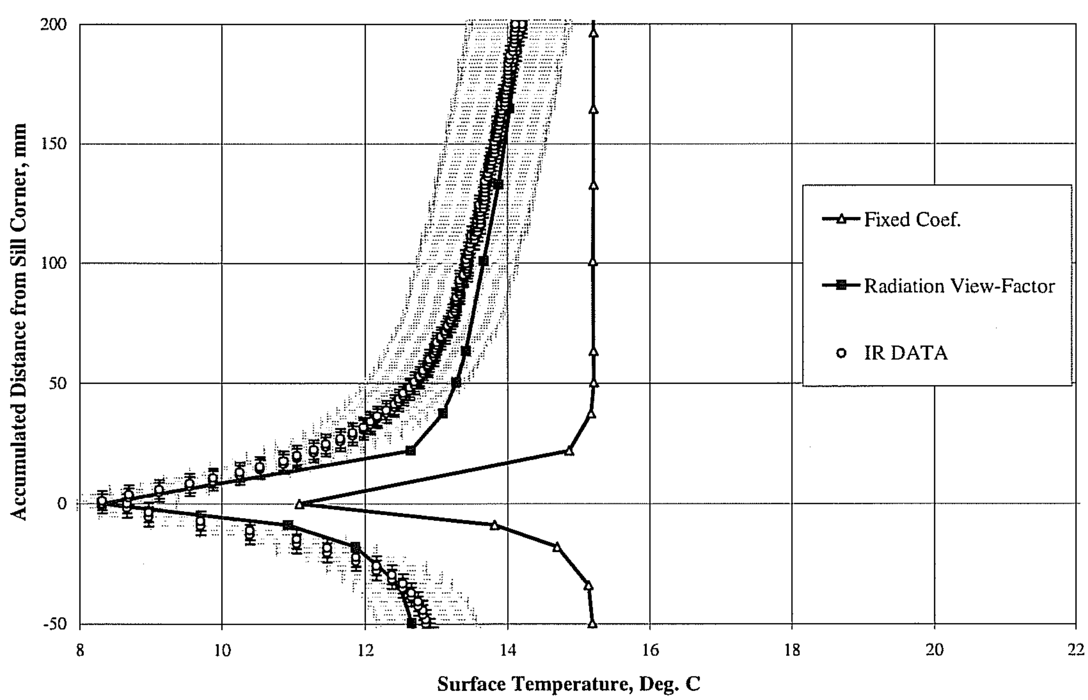

Figure 5 *Surface temperature of foam garden window at sill corner.*

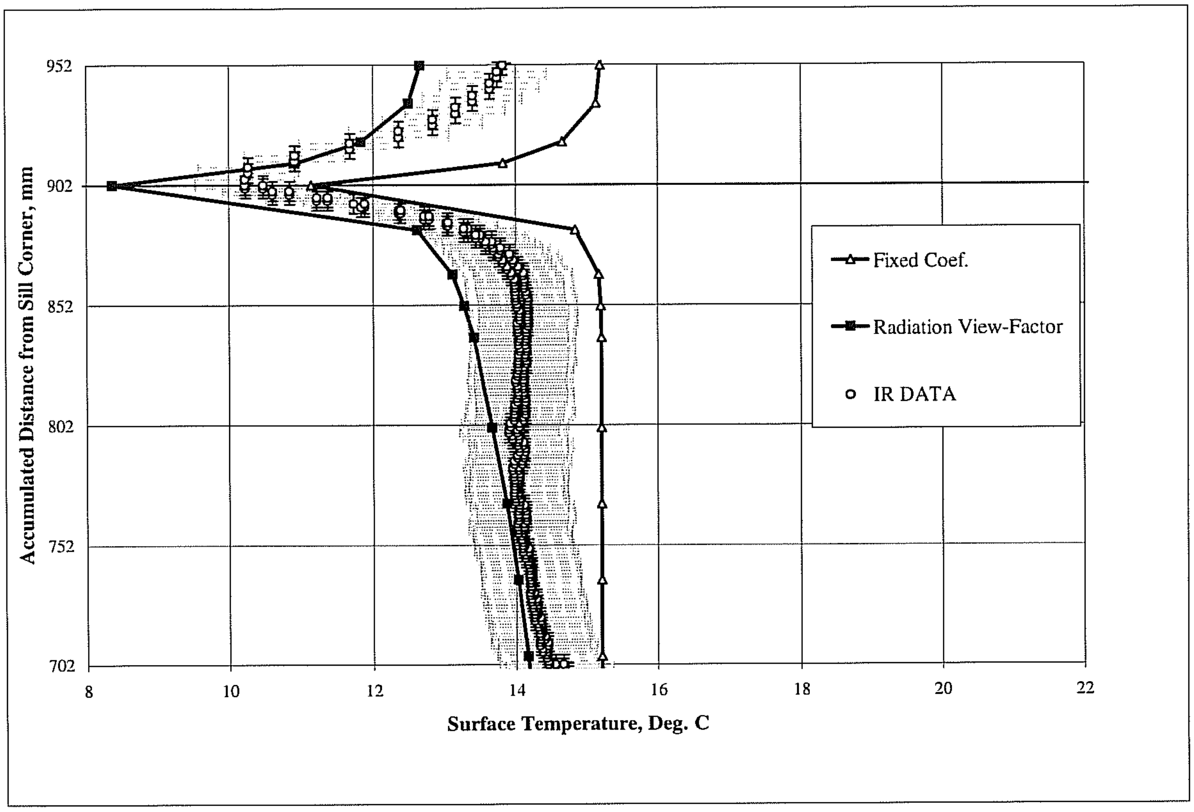

Figure 6 *Surface temperature of foam garden window at head corner.*

entire plane. Uncertainty in location values is estimated at ±1 mm.

Figure 7 shows the distribution of air temperatures. The horizontal axis locates distance from the main face. The vertical axis locates distance from the sill face. A separate gray-level/temperature scale shows the relation between shading and temperature. Absolute accuracy of thermocouple readings is estimated at ±0.3°C.

This level of accuracy was obtained by calibrating the whole measurement system at the operating temperature conditions. The system consists of a special-limits thermocouple, an isothermal zone box (thick aluminum construction), thermistors (inside zone box, also individually calibrated), and a 12 bit analog to digital converter. Calibrations were performed using a temperature-controlled fluid bath and a 100 ohm platinum resistance thermometer (4 wire technique) that had an absolute accuracy of 0.01°C.

Figure 8 shows preliminary results of velocity measurements in the air well. The spatial locations are the same as in Figure 7. The velocity values are time-averaged magnitudes of the vertical component of airflow. The air velocity data are estimated to have an absolute accuracy of ±0.3m/s based on manufacturer's specifications. Since the magnitude of the measurements was below this, we estimated it would be informative to estimate the repeatability of measurements in our laboratory; the repeatability was estimated at 0.08 m/s.

U-Factors

Table 4 summarizes the U-factor results from both the fixed-coefficient method of simulating window performance and the more complex radiation view-factor method of simulation. Because the majority of real projecting fenestration products have lower performance levels than the foam garden window, we performed additional simulations that used a higher value for thermal conductivity of the foam. The added runs, called "high-k" simulations, used a thermal conductivity of 0.06 $W/m^2 \cdot K$ in contrast to the "normal-k" simulations, which used a thermal conductivity of 0.03 $W/m^2 \cdot K$ as shown in Table 2. All other model parameters remained the same for the high-k simulations.

DISCUSSION

Local Temperature Validation

The high resolution of the IR measurements provides temperature curves with more data points than are contained in the computer models, which aids in evaluating the models. For example, Figure 5 focuses on the window's sill corner region where the IR data show greater symmetry about the corner in the first 50 mm than do the simulated data. This difference may indicate that equal-sized elements on each side of the corner might help the simulation. The error bands plotted in Figures 5 and 6 appear to show that uncertainty (±4 mm and ±0.7°C) is low enough to resolve the effects of changes in the modeling technique.

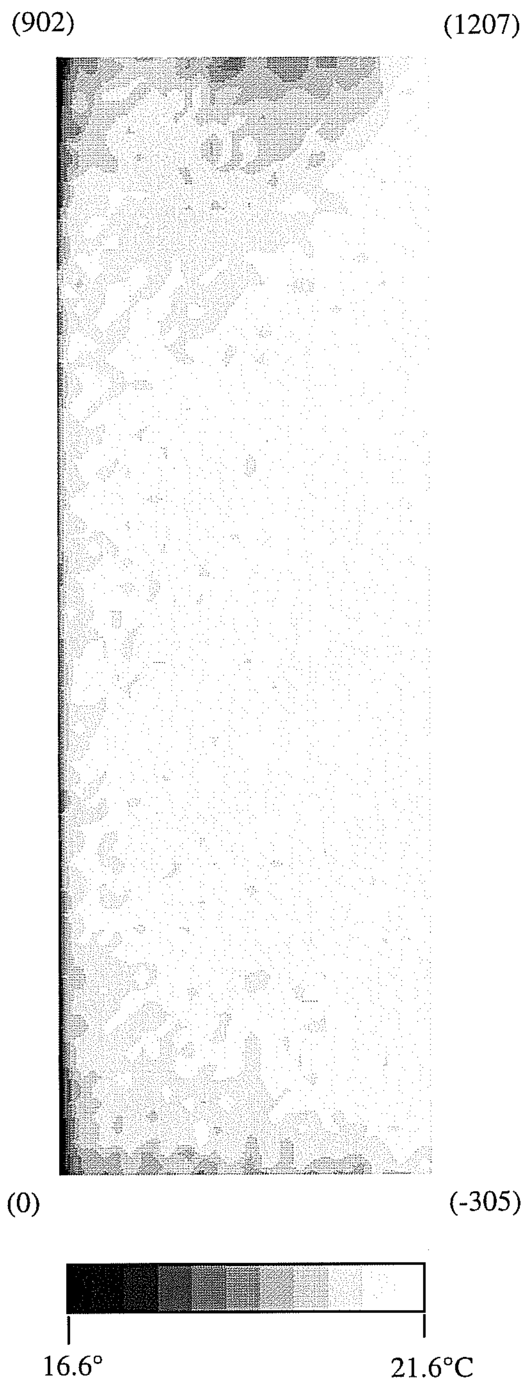

Figure 7 *Measurement-plane air temperatures in foam garden window.*

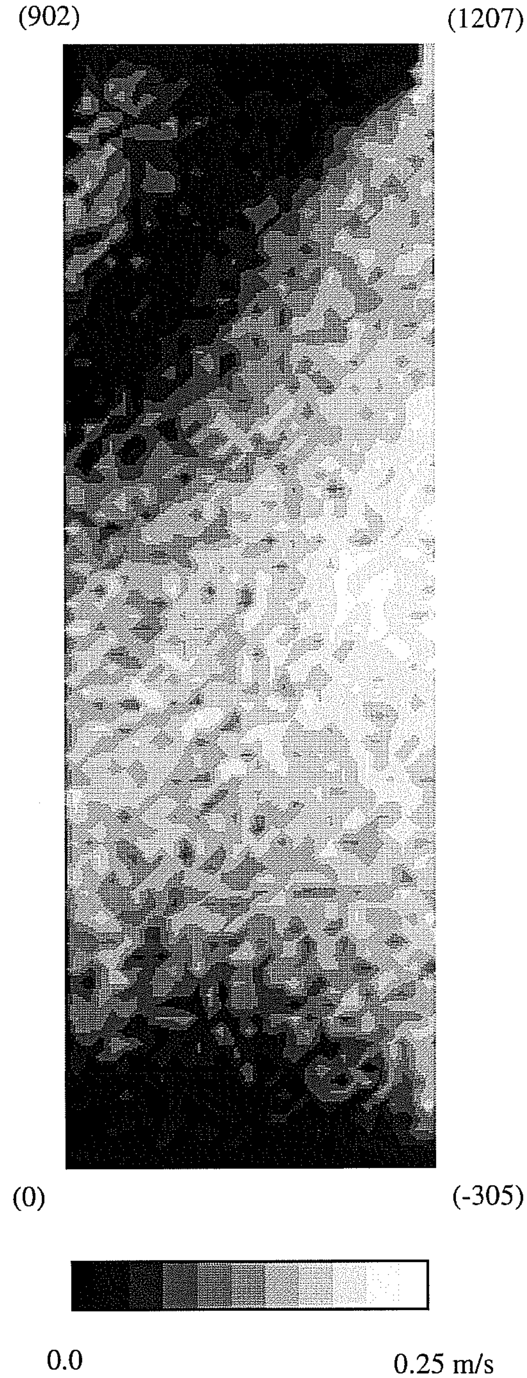

Figure 8 *Measurement-plane air velocity (vertical component) in foam garden window.*

Radiation Modeling

Comparing the temperature curves in Figure 4 shows that simulation results more closely match experimental results when the model uses a radiation view-factor analysis rather than a fixed overall coefficient for the boundary condition. The fixed-coefficient model results typically deviate by about 2°C with maximum deviations of about 3°C. The radiation view-factor model results agree fairly well with IR data for the lower portions of the specimen; most deviation is less than the level of uncertainty in the experimental data. For the upper portions of the specimen, there is significant disagreement between the radiation view-factor model's results and the IR data, with deviations of up to 1.5°C. However, the overall shape of the radiation model's temperature curve for the upper portions of the specimen is considerably more accurate than

TABLE 4
U-Factor Results for Different Simulations of Foam Garden Window

Type of Simulation	Normal-k Simulation Overall U-Factor ($W/m^2 \cdot K$)	High-k Simulation Overall U-Factor ($W/m^2 \cdot K$)
Fixed Coefficient (THERM 1.02)	1.86	2.96
Radiation View-Factor (THERM 2.0)	1.75	2.71

the shape of the curve from the fixed coefficient model. The remaining disagreement between the experimental data and the radiation view-factor model, which uses a fixed convection coefficient, probably is caused by the localized convection effects discussed below.

U-Factor

Because heat transfer simulations are performed to generate U-factors for use in rating and labeling fenestration products, it is useful to assess the effect of each modeling technique on the overall U-factor result. Table 4 shows that including surface radiation analysis in the model reduces the U-factor result by 5% to 10%. The improved simulation results come from calculating lower net radiation exchange at the warm-side surface. For real projecting windows and similar products, including radiation effects will improve the accuracy of simulated U-factors. The magnitude of the change will be more significant for lower-performance products. The foam garden window is a relatively high-performance sample; however, some real garden window products, especially those that are poorly insulated, will show an improvement greater than 10% when radiation effects are included in simulations.

Convection

Surface temperatures are cooler on the lower portions of the specimen than on the upper portion, which is consistent with expected localized effects of natural convection. However, measurements of surface temperature and window well air conditions reveal some interesting features of airflow and its effect on convective heat transfer for a projecting window. The head face of the foam garden window is oriented horizontally, and heat flow is directed upward. Thus, higher convective heat-flow rates would be expected at the head face as cooled air can easily fall away from the surface. The largest differences (<1.5°C) between the experimental surface temperature data and the radiation view-factor modeled data occur here, which helps confirm that the use of a fixed convection film coefficient is causing error in the model. The overall shapes of the modeled temperature curves in this region also do not agree with the IR data, which indicates that a different constant value may not improve the modeled results; a more complex treatment of convection in the model is necessary to match experimental results.

The IR data show the presence of unusual air flow along the top of the window's main face. Natural convection along the warm side of windows usually causes air to move downward, but, for the foam garden window, air is flowing upward along the upper 200 mm of the main face. This phenomenon is evident from the velocity distribution in Figure 8, which shows a band of very low-velocity airflow that meets the main face at about 700 mm from the sill, and from the unusual shape of the surface temperature curve at 700 mm in Figure 4. Qualitative smoke visualization tests also showed upward flow. The likely driving force for the upward airflow is continuity requirements along the head face where air that is being cooled and descending into the air well is replaced by rising air. Thus, it appears that a zone with partially recirculating flow is present in the head corner. Because the radiation view-factor modeled data deviate from the experimental surface-temperature data in this same region, we can conclude that the cause is significant localized variation in convective heat transfer. Also, as is the case for the head face, the overall temperature-curve shapes do not agree for the top half of the window's main face. A more complex treatment of convection in the model is needed to improve results.

The experimental chambers control ambient air temperatures to within about ±0.2°C of the 21.1°C set point. The accepted tolerance for deviating from the set point in experiments like this one usually is ±0.5°C. However, the data in Figure 7 show lower temperatures are developing inside the air well. Analyzing the entire data set shows that 28% of the air well is below 20.6°C. Cooler air temperatures are expected to develop near the specimen, however, because of heat flow and the associated boundary layer. For normal planar thermal specimens, a sample at a distance of 75 mm (3 in.) from the surface usually is considered far enough away to represent bulk air temperature. Analyzing the data in Figure 7 for the portion that is at least 75 mm from any surface shows that about 9% of the air is still below 20.6°C. This cooler "out-of-tolerance" air is concentrated mostly in the apparent recirculation zone at the head corner. These types of data could be useful for developing increasingly accurate, complex models of convection for projecting fenestration products.

FUTURE RESEARCH

The results presented in this paper are part of an ongoing effort to improve models of window heat transfer and methods of validating their accuracy. Future research activities directly related to the current paper are listed below.

1. THERM 2.0 is being developed to provide improved special-purpose software tools for routine analysis of window products. Besides the radiation view-factor analysis discussed here, THERM 2.0 will also be able to use convection coefficients that can vary as boundary conditions.

2. Research will attempt to determine how models can be improved by using variable-convection film coefficients to account for localized airflow effects and what methods can determine suitable variable coefficients.
3. The foam garden window specimen is being modeled in greater detail with a sophisticated computational fluid dynamics (CFD) program.
4. Additional experiments with the foam garden window are planned to better measure distribution of air velocities in order to validate the CFD simulation.
5. The effect on overall U-factor from incorporating radiation view-factor modeling and local convection film coefficients needs to be validated with hotbox measurements.
6. Development of infrared thermographic techniques will continue, focusing on verifying the accuracy of measurements that need complex background corrections and developing techniques applicable to diffusely reflecting surfaces.

CONCLUSIONS

Conducting simulations and experiments of the heat flow through a foam garden window specimen yields the following conclusions:

1. Infrared thermography can be used to measure temperatures of specimens with self-viewing surfaces and is useful for evaluating the accuracy of heat-transfer models.
2. Significant deviations (up to 3°C) exist in local temperature values between measurements and simulations when simulations of projecting windows use constant/mean film coefficients for boundary conditions.
3. The use of radiation view-factor modeling in simulations can improve the accuracy of the models and will tend to lower results for U-factors for projecting windows (skylights, greenhouse windows) and similar fenestration.
4. More research is needed to enable models to account for localized variations in convection film coefficients.

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REFERENCES

Arasteh, D., E.U. Finlayson, and C. Huizenga. 1993. *Window 4.1: A PC program for analyzing window thermal performance in accordance with standard NFRC procedures*. LBL Report 35298, Lawrence Berkeley National Laboratory, Berkeley, Calif.

Curcija, D. 1997. Computer simulation of radiation heat transfer in fenestration systems. Draft technical report 9702. Carli, Inc., Amherst, Mass.

Curcija, D. 1992. Three-dimensional finite element model of overall, nighttime heat transfer through fenestration systems. Ph.D. dissertation, University of Massachusetts, Amherst.

de Abreu, P., R. Fraser, H. Sullivan, and J. Wright. 1996. A study of insulated glazing unit surface temperature profiles using two-dimensional computer simulation. *ASHRAE Transactions* 102(2): 497-507. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.

EE. 1991. FRAME™—a computer program to evaluate the thermal performance of window frame systems, version 3.0. Enermodal Engineering Ltd. Waterloo, Ontario.

Finlayson, E.U., D. Arasteh, C. Huizenga, D. Curcija, M. Beall, and R. Mitchell. 1996. *THERM 1.0: Program description*. LBL Report 37371, Lawrence Berkeley National Laboratory, Berkeley, Calif.

Finlayson, E., D. Arasteh, C. Huizenga, M. Rubin, S. Reilly. 1993. Window 4.0: Documentation of calculation procedures. LBL-33943, Window and Daylighting Group, Lawrence Berkeley Laboratory, Berkeley, Calif.

Finlayson, E., D. Arasteh, M. Rubin, J. Sadlier, R. Sullivan, C. Huizenga, D. Curcija, and M. Beall. 1995. Advancements in thermal and optical simulations of fenestration systems: The development of WINDOW 5. In *Thermal Performance of the Exterior of Envelopes of Buildings VI*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Griffith, B.T., D. Türler, and D. Arasteh. 1996. Surface temperatures of insulated glazing units: Infrared thermography laboratory measurements, *ASHRAE Transactions* 102(2): 479-488. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.

Griffith, B.T., F. Beck, D. Arasteh; and D. Türler. 1995. Issues associated with the use of infrared thermography for experimental testing of insulated systems. In *Thermal Performance of the Exterior Envelopes of Buildings VI*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Hottel, H.C., and A.F. Sarofim. 1967. *Radiative transfer*. New York: McGraw Hill.

Shapiro, A.B. 1983. FACET—A radiation view factor computer code for axisymmetric, two-dimensional planar, and three-dimensional geometries with shadowing. Livermore, Calif.: Lawrence Livermore National Laboratory.

Shapiro, A.B. 1986. TOPAZ2D—A two-dimensional finite element code for heat transfer analysis, electrostatic, and magnetostatic problems. Rept. UCID-20824, Livermore, Calif.: Lawrence Livermore National Laboratory. July 1986.

Shapiro, A.B. 1993. TOPAZ2D computer program, revision 9/9/93. Livermore, Calif.: Lawrence Livermore National Laboratory.

Türler, D., B. Griffith, and D. Arasteh. 1997. Laboratory procedures for using infrared thermography to validate heat transfer models. *Insulation Materials: Testing and Applications: Third Volume,* ASTM STP 1320. R. S. Graves and R. R. Zarr, eds. Philadelphia, Pa.: American Society for Testing and Materials.

UW. 1992. *VISION3: Glazing system thermal analysis—Reference manual.* Waterloo, Ontario: Advanced Glazing System Laboratory, University of Waterloo.

WIS. 1994. Advanced window information system: Software version 1.0. Energy Research Group, University College Dublin.

Zhao, Y., D. Curcija, and W. Goss. 1996. Condensation resistance validation project—Detailed computer simulations using finite element methods. *ASHRAE Transactions* 102(2) 508-515. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.

DISCUSSION

Roydon Fraser, Doctor, University of Waterloo, Waterloo, Canada: How fortuitous vs. how tied to previous experiments is the result that the therm results (with and without radiation viewing considerations) span the temperature data? Why did you not force the total U-factor to be the same between heat-transfer coefficients determining experiment and the simulations?

Brent Griffith: We did not want to force U-factors to be the same because we wish to determine the effect that different ways of simulating the surface heat transfer have on U-factor results. The comparisons focused on surface temperatures, which are strongly influenced by the surface heat transfer rates, or film coefficients. The values used in the simulations for mean film coefficients (where applicable) were derived from separate experiments that tested a planer calibrated transfer standard (CTS) in the chambers. This ties the general performance of the chamber to the simulations. However, the projecting specimen analyzed in the paper differs from the flat CTS and probably had very different film coefficients but we have no way of directly measuring them. Since the simulation results did turn out to span the experimental results, we can conclude that the fortuitous situation existed where the features of the specimen were such that the "as tested" coefficients (on average) did not show extreme differences from the situation during the CTS test. The paper attempts to point out that significant differences do exist locally.

Michael Glover, Principal, Bowmead Technology Ltd., Ottawa, Ontario: Was the impact of curtains and other "real life" window attachments taken into account when developing the guidelines for modeling projecting fenestration products?

Brent Griffith: I believe the answer would be no. If they were taken into account, such attachments would tend to exasperate the radiation situation making it more important to directly model thermal radiation in order to obtain an accurate simulation.